Gallium Arsenide Charged Particle Detectors: Deep Levels Effects

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Abstract

This paper deals with the interpretation of the charge-collection efficiency for minimum ionizing particles in terms of electron traps in semi-insulating liquid encapsuled Czochralski Gallium Arsenide detectors fabricated on wafers of different origin.

A normalized double-gate photo-induced current transient spectroscopy has been carried out to get information on the activation energy, capture cross section and density of the defects. The results show that the low charge-collection efficency (75%) cannot be ascribed only to the presence of high concentrations of the EL2 defects.

Introduction

Gallium Arsenide Schottky detectors made of commerciale undoped semi-insulating (SI) liquid encapsulated Czochralski (LEC) material have been shown to work as charged-particle detectors, with essential 100% detection efficency for ionizing particles.

Moreover the detectors have proved able to withstand radiation levels up to 50Mrad gamma rays and 7×10^{14} neutrons per cm^2, without severe degradation[1].

In spite of this very sactisfactory property, the charge-collection efficiency (cce) is found to be less than 100% and this loss has been ascribed to the presence in the materials of deep levels which are responsabile for the trapping of a fraction of the charge carriers[2].

In this work an attempt has been made to correlate the deep level densities with the charge collection using samples of LEC SI GaAs with different trap densities.

Experimental Procedure

The detectors were made of undoped SI LEC <100> GaAs wafers supplied by SUMITOMO and processed by ALENIA (which are hereafter called SL96) and those supplied by the MASPEC-CNR laboratory and processed at the Istituto Nazionale di Fisica Nucleare (INFN) Laboratory at the Bologna section of the INFN (which are hereafter called LPA114/9 and LPA114/95).

An Au-Ge-Ni metallization process was used as alloyed ohmic contact for the SL96 specimen, while non-alloyed ohmic contacts by a solid phase epitaxy growth of a n^+-Si layer on n-type GaAs were used for the other samples. The Scottky contact was realized by means of a circular dot of thin titanum film (~1000Å). The details of the processes have been described elsewhere[3].

Resistivity (n-type) and Hall mobility at room temperature of the wafers examined are reported in Table1.

	LPA114/9	LPA114/95	SL96
μ_{Hall} (cm^2/Vs)	5800	2800	6900
ρ (Ωcm)	1.5×10^7	4.2×10^6	5.2×10^7

Table I: Hall mobility and resistivity at room temperature of the wafers examined.

The cce was measured with the betas of a ^{106}Ru source as minimun ionizing particles, with the ohmic and the Schottky contatcts of the GaAs detector grounded and set at a negative voltage, respectively. The signals, obtained at the Schottky contatcts were amplified and shaped for a multichannel analyser[4].

The thermal activation energy, the capture cross sections and the concentrations of the traps were determined by using photo-induced current transient spectroscopy (PICTS)[5]. The details of the measurements have been described elsewhere[6].

Results and Discussion

The cce monotonically increases when the applied voltage is increased (Fig.1) but it always remains less than 100%. The maximum value of the cce, measured at the breakdown voltage, is 34%, 56% and 75% for the LPA114/9, LPA114/95 and SL96 specimens, respectively.

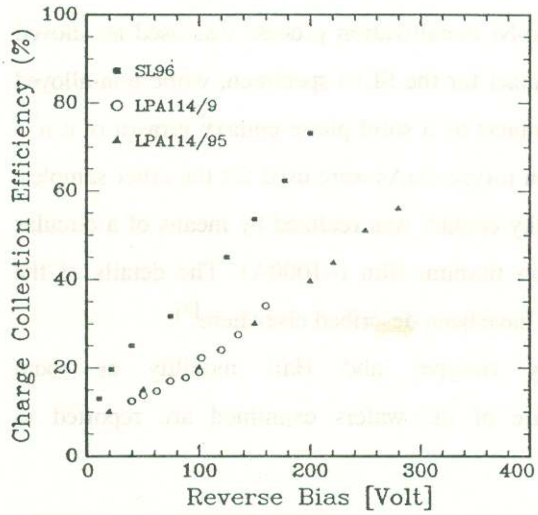

Fig.I: Charge-collection efficiency for minimum ionizing particle as a function of reverse bias in the specimens of Tasble III.

A possible explanation of these results can be found in the crystal purity of this material. SI LEC GaAs material is in fact compensated by a balance of deep donors with shallow acceptor impurities[7].The deep donor levels, which are not fully ionized in thermal equilibrium, became ionized when a reverse bias is applied to the Schottky contact and start to trap most free charge carriers[8]. Then, in order to understand the operating behaviour of the device, it is essential to achive an accurate knowledge of the traps present in the material in terms of activation energy and concentrations. These parameters have been measured for SL96, LPA114/9 and LPA114/95 specimens by means of the PICTS technique[5]. Five traps have been identified in each sample; the relative activation energy, capture cross section and density are reported in Table II and III, respectively.

ACTIVATION ENERGY (eV)	CROSS SECTION (cm^2)
0.17-0.18	4.5×10^{-15}-3.5×10^{-14}
0.30-0.33	2.9×10^{-13}-7.7×10^{-13}
0.39-0.41	8.3×10^{-13}-2.2×10^{-12}
0.53-0.58	8.3×10^{-13}-8.3×10^{-12}
0.74-0.82	5.3×10^{-13}-3.3×10^{-12}

Table II: Activation energy and capture cross section of the traps in the specimens examined.

TRAP CONCENTRATION (cm^{-3})					
Ea (eV) / Sample	0.17-0.18	0.30-0.33	0.39-0.41	0.53-0.58	0.74-0.82
SL96	9.1×10^{14}	1.5×10^{15}	1.7×10^{13}	6.6×10^{14}	1.3×10^{15}
LPA114/9	8.2×10^{13}	1.4×10^{14}	3.6×10^{13}	8.1×10^{14}	1.8×10^{15}
LPA144/95	8.7×10^{13}	9.2×10^{13}	4.7×10^{13}	8.4×10^{13}	4.5×10^{15}

Table III: Concentration of the traps in the specimes examined.

The correlation betweeen trap concentrations and cce for the three specimens is shown in Fig.2.

The main features of this analysis are that:

i) the traps are electron traps and their energy levels are measured from the conduction band level,

ii) the trap of 0.41eV is present in SL96 specimens at very low density ($<10^{13}$ cm^{-3});

iii) the density of EL2 (0.75 eV) takes the lowest value in the SL96 specimens;

iv) the trap at 0.18eV is present at concentrations of the same order of magnitude as EL2 in SL96 specimens and almost one order of magnitude lower in LPA114/9 and LPA114/95 samples.

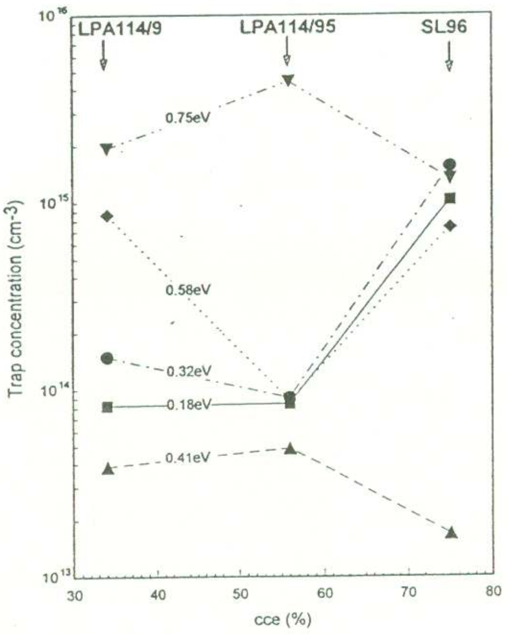

Fig.2: Traps concentration as a function of the charge-collection efficiency for minimum ionizing particles in the specimens of Fig.1.

These features seem to support the idea that the experimental limitation in the cce observed in these materials (Fig.1) cannot only be ascribed to the presence of the deep level EL2, which is often assumed to play the leading role[8], but also to the defects in their totality. In fact, all donors which lie in thermal equilibrium, near the Fermi energy level in the bulk of the detector, will be ionized when the band bending is increased by the application of the reverse bias to the Schottky barrier. The shallow donors, however, can provide the electrons to campensate the ionized deep levels[9], so that these latter become neutral defects and cannot trap charge carriers[10,11].

Therefore a possible explanation of the significant differences observed between the values of charge collection efficiency in different materials with nearly the same density of EL2, can be ascribed to different concentrations of deep donor-like states E_T shallower than EL2, which assist the transition of the deep EL2 from its ionized state $EL2^+$ to the neutral state $EL2^0$ (Fig.3). In this respect, it is to be noticed that the sample with the largest cce is SL96, i.e. the material with the highest density of traps at 0.18 and 0.32 eV from the conduction band. Namely in this material these traps could compensate for the $EL2^+$ defects in the widest way.

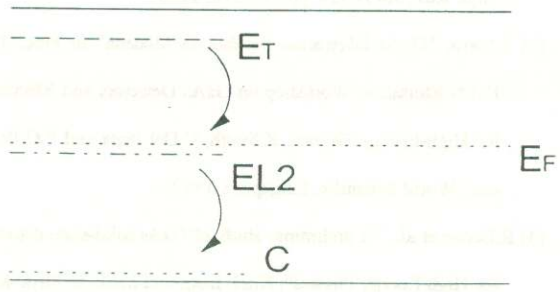

Fig.3: Compensation mechanism model with the shallow carbon acceptors C, which would exist in the starting material.

Conclusion

Studies with mimimun ionizing particles have shown that GaAs detectors have an acceptable performance in detection efficiency; however the charge collection efficiency is less than 100%.

The comparison between the operation of particle detectors realized with bulk SI GaAs using different materials seems to indicate that the deleterious effect on the operation is to be expected from the ionized mid-gap electron traps, which are not perfectly compensated by the shallow-donor like defects.

The obvious next step is to fabricate detectors from material with a lower and equal concentration of deep donor and shallow dopant impurities and to use new proccesses in order to improve the diode barrier heights and to reduce the ohmic conctat resistance.

It is believed, in fact, that the non-compensated deep level donors in the material and the high ohmic contact resistence are severely affecting the electric field distribution and then the cce.

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